

System Level Analysis of a Water PCM HX Integrated into Orion's Thermal Control System Abstract

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In a cyclical heat load environment such as low Lunar orbit, a spacecraft's radiators are not sized to reject the full heat load requirement. Traditionally, a supplemental heat rejection device (SHReD) such as an evaporator or sublimator is used to act as a "topper" to meet the additional heat rejection demands. Utilizing a Phase Change Material (PCM) heat exchanger (HX) as a SHReD provides an attractive alternative to evaporators and sublimators as PCM HXs do not use a consumable, thereby leading to reduced launch mass and volume requirements. In continued pursuit of water PCM HX development an Orion system level analysis was performed using Thermal Desktop for a water PCM HX integrated into Orion's thermal control system in a 100km Lunar orbit. The study verified the thermal model by using a wax PCM and analyzed 1) placing the PCM on the Internal Thermal Control System (ITCS) versus the External Thermal Control System (ETCS) 2) use of 30/70 PGW versus 50/50 PGW and 3) increasing the radiator area in order to reduce PCM freeze times. The analysis showed that for the assumed operating and boundary conditions utilizing a water PCM HX on Orion is not a viable option for any case. Additionally, it was found that the radiator area would have to be increased by at least 40% in order to support a viable water-based PCM HX.

Nomenclature

<i>ETCS</i>	= external thermal control system
<i>HX</i>	= heat exchanger
<i>IFHX</i>	= interface heat exchanger
<i>ITCS</i>	= internal thermal control system
<i>PCM</i>	= phase change material
<i>PGW</i>	= propylene glycol water
<i>SHReD</i>	= supplemental heat rejection device
<i>TCS</i>	= thermal control system

I. Introduction

Water-based Phase Change Material (PCM) Heat Exchangers (HX) are currently being investigated for use on Orion. Traditionally, paraffin type phase change materials have been used on spacecraft but water is an attractive alternative PCM. Water is advantageous for use as a PCM due to water's large heat of fusion. When compared to n-pentadecane, the baseline wax for Orion, water is capable of storing about 1.6 times more energy than wax. The heat of fusion for n-pentadecane is 200 kJ/kg, whereas the heat of fusion for water is 333 kJ/kg. Thus, by increasing the amount of energy storage per unit mass, water has potential to significantly reduce a HX's mass and volume requirements. While there is a significant advantage to using water as a PCM and numerous experimental studies have been completed, a detailed analysis of the integration of a water-PCM into Orion's

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thermal control system has not been studied¹⁻¹⁰. This paper reports on integration of a water PCM HX into Orion's thermal control system and the associated challenges by using thermal desktop and python.

II. Orion's Thermal Control System and PCM Location

Figure 1 shows a simplified version of Orion's Thermal Control System. It consists of a two loop system comprised of an Internal Thermal Control System (ITCS) and External Thermal Control System (ETCS). The ETCS typically flows ammonia or a low temperature fluid which flows through the Interface

Heat Exchanger (IFHX) to pick up a heat load from the ITCS. Next the fluid flows

through radiators which are typically facing the coldness of space and are able to reject large amounts of heat.

On the ITCS, it is important to note that T_{set} represents the internal thermal control system set-point temperature of the vehicle. This typically ranges from 8-12°C. From this set-point temperature thermal control fluid travels through coldplates and other heat acquisition and fluid temperature increases. Next, the fluid passes through a bypass valve where fluid either continues on to the IFHX (for heat exchange with the ETCS) or is diverted via bypass where hot fluid is mixed with cold fluid flowing from the IFHX to maintain the system set-point temperature.

PCM's are positioned after the IFHX to provide supplemental cooling to the vehicle when the vehicle is in high heat sink environments (sub-solar point) and the radiators cannot provide adequate cooling. Typically, the latent phase change of paraffin wax inside the HX's are selected based on system set-point temperatures. Thus, no or little mixing is required by the bypass valve positioned after the PCM and the system set-point temperature is maintained.

Maintaining this set-point temperature of 8-12°C while using water-based PCM requires active control. This is due to water's latent phase change temperature of 0°C. Thus, water flowing out of the PCM, must be warmed from 0°C to 8-12°C to maintain system set-point temperatures. Additionally, because water's phase change temperature is lower than wax, less freezing capacity is available for water PCM's when compared to wax (Figure 2). This may lead to the PCM not being able to fully freeze in 120 orbit with about 90 mins available for freezing and about 30 minutes available for melting and is a main thrust of this paper.

In order maximize the amount of freezing time and minimize the amount of thawing time available to the PCM a bypass was added around the PCM to the thermal models discussed in this paper. This created the three different flow rates to the PCM depending on PCM inlet temperature to maximize freezing potential (Table 1).

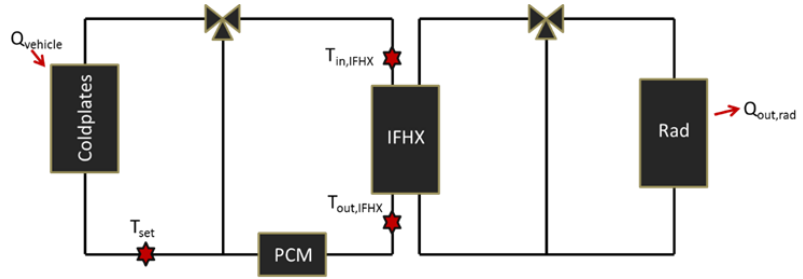


Figure 2. Simplified Orion thermal control system.

Table 1. Flow conditions with PCM bypass valve.

Temperature Condition	Flow Condition
If $T_{out,IFHX} < 0^{\circ}\text{C}$	PCM Full Flow
If $0^{\circ}\text{C} < T_{out,IFHX} < 8^{\circ}\text{C}$	PCM Full Bypass
If $T_{out,IFHX} > 8^{\circ}\text{C}$	PCM Partial Bypass controlling to $T_{out,PCM}=12^{\circ}\text{C}$

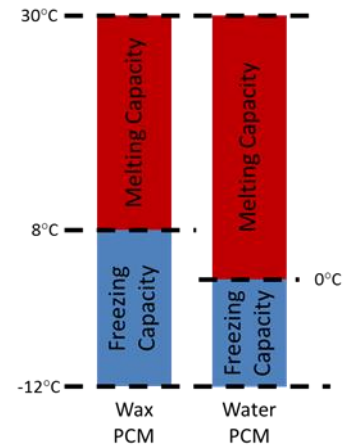


Figure 2. Freezing capacity available to water and wax PCM's.

III. Thermal Model Development and Assumptions

To determine if a water-based PCM HX can freeze and melt during a 120 minute orbit for multiple orbits, analysis was completed with a Thermal Desktop Model and a simplified model written in Python. Four cases were modeled in this study

1. Verification of the thermal model by comparing wax and water PCM's
2. Placing the PCM on the ITCS loop versus the External Thermal Control System (ETCS) Loop
3. Using a 50/50 propylene glycol water (PGW) mixture versus a 30/70 PGW mixture
4. Increasing the radiator area in order to reduce the PCM freeze times

For this analysis, Lockheed's Thermal Desktop model of Orion's radiator was used. The radiator used in this model is composed of seven panels in series with total radiator area of 20.25 m² with an emissivity of 0.89. This emissivity was reduced by half to model half of the radiator, as two loops comprise the TCS on Orion. The radiators were also modeled as aluminum 6060-T6 and divided in half to reduce the radiator mass by half (20 total kg modeled). This was done for the same reason as emissivity. Sink temperatures used were calculated for a sphere in a 100km lunar orbit (Figure #). Flow rate for the system was modeled as 234 lbm/hr for the ITCS. HFE 7200 was used for the working fluid of the ETCS and a flow rate of 1,275 lbm/hr was used. System heat load was 2205 W. Additionally, a system mass of 18kg was used for the ITCS loop and 18kg for the ETCS loop (Ochoa and Vonau 2009 ICES paper assumed a total of 66 kg of plumbing and fluid mass for a two-loop ATCS design). The PCM was modeled as weighing 23 kg (11.5 kg water and 11.5 kg stainless steel) and it assumes a HX efficiency of 95% Model assumptions included an 8.3°C ITCS set-point prior to system heat loading and a 12°C system set point during supplemental heat rejection events.

IV. Verification of Thermal Model and Analysis Cases

A. Model Development and use of Wax PCM

The goal of this analysis was to determine if the model to be used for water-based PCM's provides accurate results. Thus a wax PCM, which is known to maintain the ITCS set-point temperature for the modeling assumptions provided, was used in the thermal desktop model. For this analysis, all the same modeling assumptions were used, however, the system heat load was reduced from 2205 W to 1900W. Additionally, a PCM bypass valve was used for the water PCM but not the wax PC. Figure 3 provides 20 hours of orbit time for the wax PCM and indicates that for this duration (about 10 orbits) the wax PCM provides adequate supplemental cooling to the vehicle, maintaining its ITCS setpoint temperature. This shows that the PCM thermal

desktop model is functioning correctly for the given operating conditions.

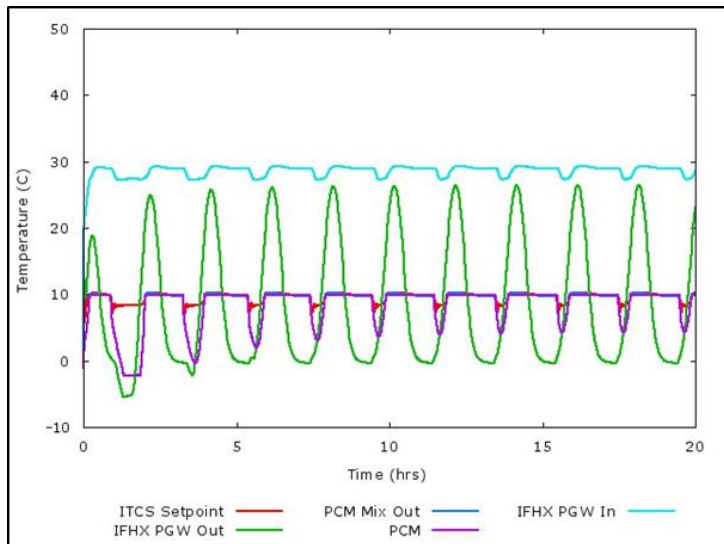


Figure 3. Temperature vs. time graph of wax PCM.

B. Comparison of Wax and Water PCM's Integrated to ITCS

For this analysis, the PCM's are integrated on the ITCS and analysis is completed using the previously described assumptions. Figure 4 indicates that the wax PCM is able to maintain the ITCS setpoint for an indefinite amount of time in this cyclical heat load environment. This also indicates the thermal desktop model developed is functioning properly, as it is given that wax PCM are capable of working on orbit. Figure 4 also indicates the water PCM's loses ITCS setpoint after about 6 hours of orbit (3 orbits). This is due to the fact that the PCM is not able to re-freeze during the cold period of orbit.

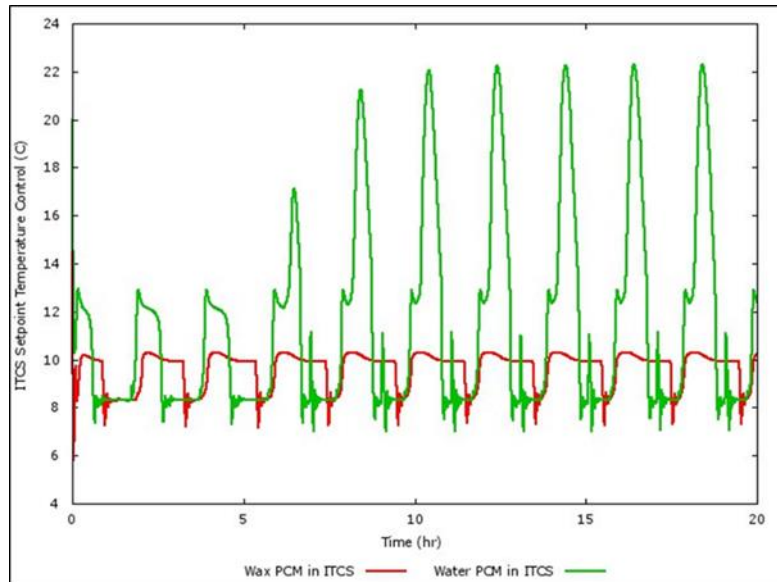


Figure 4. Temperature vs. time graph comparing water and wax PCM's.

C. PCM Integrated on ITCS

For this analysis, the PCM is integrated on the ITCS and utilizes the same PCM by-pass controller to maximize freezing and minimize thawing to the PCM that was used in the initial study. The same modeling assumptions were used as previously described, however, the system heat load was increased from 1900W to 2205W to reflect a more accurate heat load on Orion. Figures 5 and 6 indicate that the PCM is able to hold the ITCS setpoint temperature range for about 2 orbits (4 hours) before losing set-point temperature on the ITCS. This is due to the fact that the PCM does not spend adequate time in the “cold” period of the orbit and is therefore not able to freeze fully. One reason for the decrease in performance of the PCM between this model and the previously reported model is that this model uses a greater heat load than the first model, thereby reducing the effectiveness of the PCM.

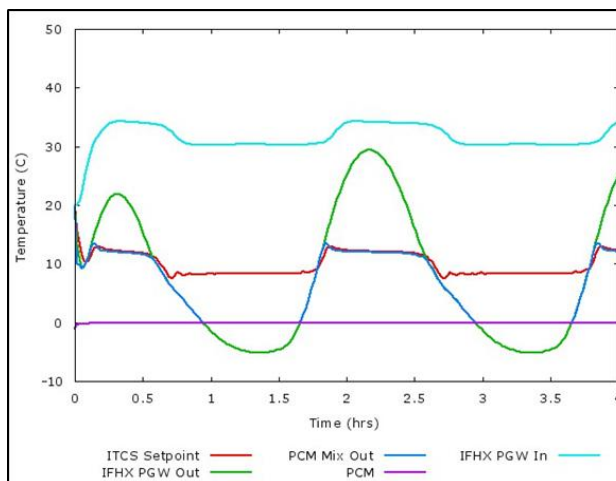


Figure 5. PCM Integrated on ITCS (Hours 0-4).

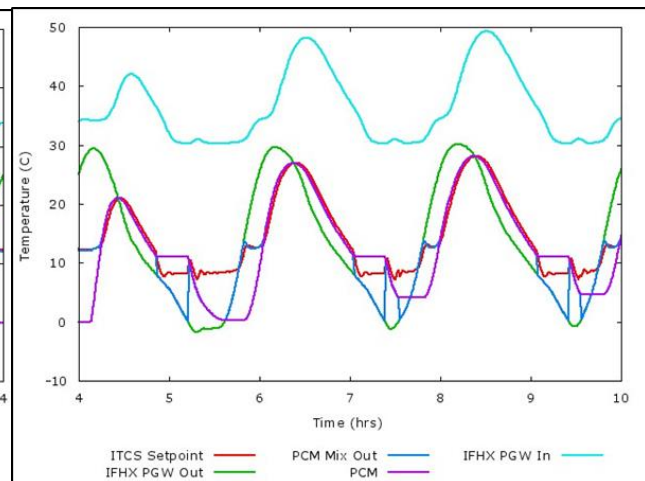


Figure 6. PCM Integrated on ITCS (Hours 4-10).

D. PCM Integrated on ETCS

For this analysis, the PCM is integrated on the ETCS. Because this loop operates at lower temperatures, the PCM bypass valve is not included. Using the previously described modeling assumptions, Figures 7 indicate that the PCM is unable to maintain ITCS set points after 2 hours of orbit (about 1 complete orbit). One reason for the shorter amount of time is **that the fluid is hotter.**

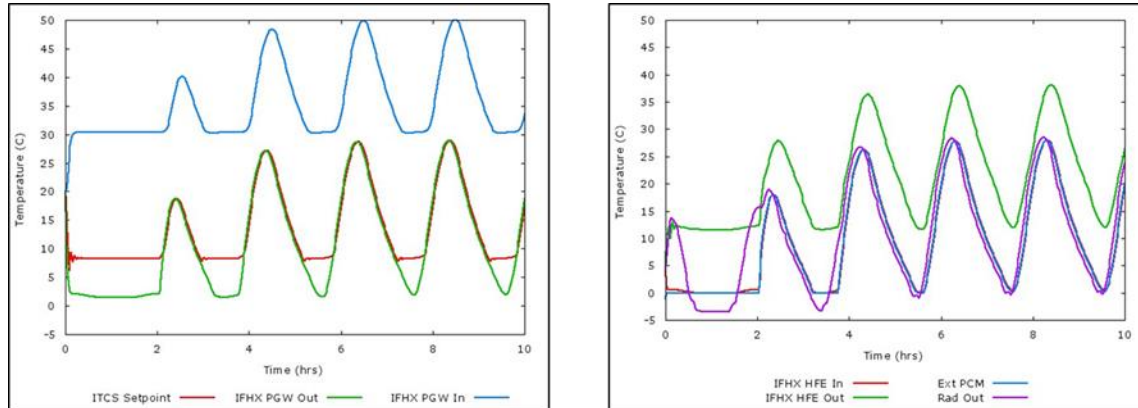


Figure 7. Temperature vs. time graphs of water PCM Integrated on ETCS (Hours 0-10).

E. PCM Utilizing 30/70 PGW

For this analysis, the typical 50/50 PGW mixture used on the ITCS was replaced with a 30/70 mixture of PGW. Moving to this mixture increases the specific heat of the thermal control fluid allowing more energy to be removed per unit mass, thereby freezing the PCM at a faster rate. Figure 8 compares the ITCS setpoint temperature for a 50/50 PGW mixture and a 30/70 PGW mixture. This change shows minimal effects of switching the thermal control fluid to 30/70 PGW as the ITCS setpoint is again lost after 4 hours of orbit.

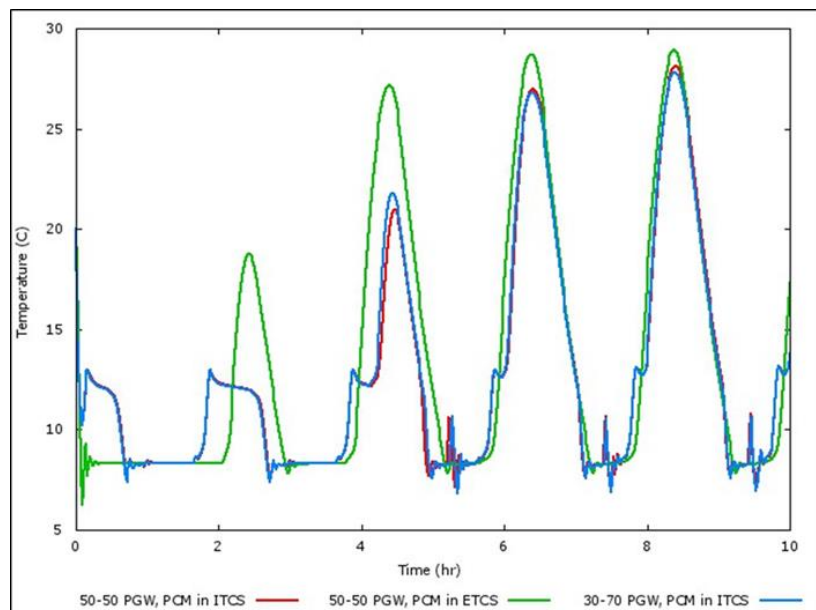


Figure 8. Comparison of using 30/70 PGW to 50/50 PGW to freeze water based PCM on ITCS.

F. Increasing Radiator Size to Decrease Thaw Times

The analysis completed thus far in the report has suggested the water PCM is not a viable option for the assumptions provided. This is mainly due to the fact that 1) the PCM does not have enough time to re-freeze during the cold period of the orbit and 2) the fluid temperature is not cold enough to provide adequate heat removal to the PCM. One option to decrease fluid temperature is to increase the radiator size. This will allow a spacecraft to reject a greater amount of heat to the environment, thus allowing working fluids to cool quicker and to a lower temperature. Thus, a study was completed to determine the radiator area increase needed to provide adequate cooling to allow the PCM to re-freeze and, in turn, maintain ITCS set-point temperature. Figure 9# highlights the results from the thermal desktop analysis performed on this system.

Analysis results show that the PCM is able to maintain system setpoint temperature only when the radiator area is increased by 40%! For the half system modeled (20kg) this translates to an additional 8 kgs of weight needed in radiator, thus negating any weight savings associated from utilizing water as a phase change material. Additionally, the added complexity and weight of a PCM bypass valve limits the viability of utilizing a water PCM.

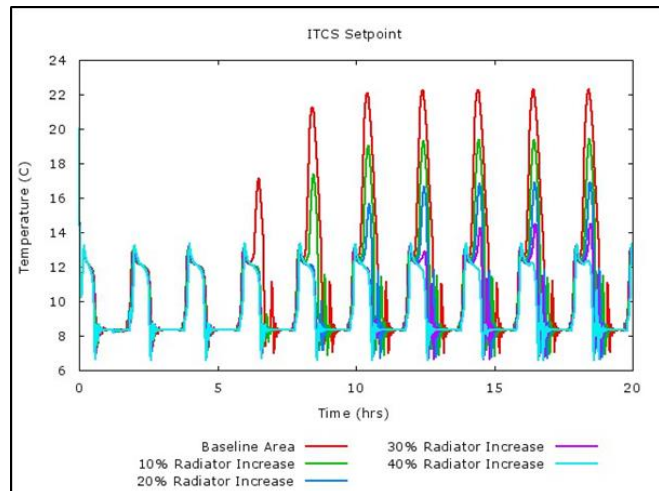


Figure 9. Impact of radiator increase on ITCS setpoint.

V. Conclusion

In summary, a system level study was completed for the integration of a PCM on a spacecraft for several scenarios including the following:

1. Verification of thermal model by comparing wax and water PCM's
2. Placing the PCM on the ITCS loop versus the External Thermal Control System (ETCS) Loop
3. Using a 50/50 propylene glycol water (PGW) mixture versus a 30/70 PGW mixture
4. Increasing the radiator area in order to reduce the PCM freeze times

For all cases, it was determined that a water PCM is not a viable option as the ITCS setpoint temperature limit is lost within at least 6 hours (3 orbits) for all cases studies. However, a possible viable option would be to increase the radiator size by at least 40%. Doing this would allow thermal control fluid to reach lower temperatures, thereby freezing the PCM quicker. However, increasing radiator area will add at least an estimated 8kg of mass to a single ITCS loop, negating any mass savings by using water instead of wax. Thus it is recommended that water PCM development not be pursued.

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